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Solar radiation manipulations and their role in greenhouse claddings: Fluorescent solar concentrators, photoselective and other materials

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ABSTRACT

Since only Photosynthetic Active Radiation (PAR) is valuable for plants, modifications of solar radiation which enters greenhouse interior space can provide several advantages. These modifications can be achieved by using specific kinds of cladding materials. The present paper refers to some claddings such as those which modify Red/Far-red (R/FR), Blue/Red (B/R), Blue/Far-red (B/FR) ratios; fluorescence solar concentrators; passive optical means; desalination roofs; anti-condensation materials; covers which diffuse sunlight and other. The authors of the present investigation, present representative studies from the literature and make criticism on each cladding category. The results reveal that there are some types of covers which have the potential to provide benefits to the greenhouse, provided these are used in a cost-effective way and several critical factors are taken into account. Moreover, the development of energy efficient greenhouses and the application of renewable energy technologies such as solar energy systems are important issues. Finally, some additional considerations regarding cladding degradation, greenhouse microclimate in conjunction with the covers etc., provide a more complete overview of the studied issues.

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1. Introduction

Ultraviolet (UV), Photosynthetic Active Radiation (PAR) and Near-Infrared (NIR) is the global solar radiation [1,2] which enters the interior space of a greenhouse. However, only PAR is crucial for plants growth and photosynthesis. Thus, claddings which modify global solar radiation can offer several advantages. In authors' previous investigation, Fresnel lenses (FL), NIR- and UV-blocking materials were presented [3] while the present article refers to more cladding types as well as to some additional considerations.

Except of FL passive systems which were presented in authors' previous work [3], other types of passive optical means e.g. reflectors [4] are included in the present paper as a separate category. The studies of this category are also not recent and the practical applicability of these systems has several difficulties.

Claddings (films or fluid roofs) which alter Red/Far-red (R/FR), Blue/Red (B/R), Blue/Far-red (B/FR) ratios are presented as a separate category. The ability of these materials to alter the above mentioned ratios can be achieved for example by incorporating pigments into the film. In this way, these films cause changes to the photomorphogenic responses of the crops and thus control plant growth [5,6]. For example an increase in plants productivity can be achieved by using specialized additives which convert UV into the red light range 600–611 nm [7]. Most plants have maximum photosynthetic sensitivity in the blue and red regions (the wavelengths for blue and red are: dark blue = 455–485 nm; light blue = 485–505 nm; red = 620–760 nm [2]). Blue light is vital for the initial stage of plants growth and during the blooming while red light is most necessary for the general growth. An appropriate balance is important because excessive FR light may lead to unwanted stem elongation. Red to Infrared (IR) regions are responsible for thermic effects, which are related with the flowering and ripening of the crops [7]. Therefore, the commercial development of these cladding materials could reduce costs for growth regulating chemicals as well as the risks for the human beings and the environment. In the literature, there are several studies about this type of coverings.

Fluorescent solar concentrators (FSCs) are another kind of claddings. Their operation is based on the following principles: one or more high quantum yield species are dissolved in a rigid and highly transparent medium of high refractive index; solar photons which enter the plate are absorbed by the luminescent species and then are reemitted in random directions. Based on Snell's law, a large fraction of the emitted photons will be trapped within the plate and transported by means of total internal reflections to the edge of the plate, where they will be converted by Photovoltaic (PV) cells [8]. Thereby, for this case parallel production of electricity can be achieved. FSCs may include new plastic films which contain fluorescent pigments and shift UV to blue or red light (colorless films) or green radiation to red light (orange-red colored films). Important parameters for this kind of films are the total light transmission, spectral distribution, fluorescent effect as well as photostability [9]. In general, FSCs seem to be a promising technology for greenhouse cladding applications and thus several studies have been reported in the literature.

On the other hand, in the literature there are few studies which refer to desalination systems (solar stills) integrated into the roof of a greenhouse [10]. During hot periods, when it is necessary to reduce the light transmission into the greenhouse, these systems can provide cooling and could be used for cultivation in places where saline or brackish water is available. For these systems their economic feasibility and the extent of the possible reduction of the incoming solar radiation should be examined.

Another category is the anti-condensation (anti-drip) claddings. The presence of condensate on the inner surface of the cover which is exposed to the plants is related with the light transmittance of the greenhouse cover. Condensation can occur frequently due to the presence of high evapotranspiration rates and low insulation in greenhouses. The nature of the condensate formed on the cladding is a crucial factor and can lead to reduction or slightly increase of the cover transmittance. Generally two kinds of condensation exist: filmwise (the water spreads out as a continuous film over the surface of the cover resulting in complete wetting) and dropwise (separate drops are formed on cladding surface: partial wetting) [11]. The anti-condensation claddings may contain specific additives for the elimination of the droplets. In the literature there are several studies about the presence of condensate on the greenhouse cover and how this phenomenon influences PAR transmittance of the cladding [12].

Claddings which diffuse sunlight are another category of greenhouse covers. Diffuse radiation penetrates deeper into plants canopy in comparison to direct light; thus, it is desirable. For example at high irradiation, diffuse greenhouse cover leads to better light distribution, lower plant temperature, decreased transpiration and increased photosynthesis and growth. The photosynthetic response of plants canopy to the conversion of PAR-direct into PAR-diffuse radiation is seasonally dependent. In addition, the PAR intercepting capacity of the plants may be diverse depending on the evolution of leaf area index in the frame of the growing season. In the literature there are some studies which refer to the relationship between greenhouse gladding materials and diffuse radiation [13].

Finally, some other types of claddings: double; zig-zag; photoselective nets are presented in a separate paragraph. Double/zig-zag claddings can provide energy savings which is crucial for the northern countries with cold winters while photoselective shade-nettings are a specific category of nets [14].

The innovation of the present study is the critical review and the complete presentation of claddings which can modify the solar radiation which enters greenhouse interior space. In this way, the present work along with authors' previous study [3] provides a comprehensive overview of several specific types of greenhouse coverings (FSCs, claddings which modify R/FR, B/R, B/FR ratios,

etc.). In addition, the criticism of the authors of the present investigation gives new perspectives and valuable insight in terms of the presented technologies. Practical applicability, cost-effectiveness and energy efficiency of the proposed systems are crucial issues and should be addressed. Finally, some additional considerations about aspects such as claddings degradation, application of solar energy technologies etc., provide a more complete picture of the studied issues.

From the types of covers which were presented in the frame of the present investigation it can be concluded that the knowledge and effective use of the several greenhouse claddings which achieve modifications of the sunlight is of importance for the growers, the scientists, the manufactures and general provides advantages in the greenhouse industry. Nevertheless, certain considerations for designing and selecting a greenhouse covering system should be taken into consideration [15] as well as energy savings strategies [16] and application of environmentally friendly technologies.

2. Claddings and sunlight manipulations

2.1. Claddings which modify red/far-red, blue/red, blue/far-red ratios

These claddings are known as “photoselective” and may include covers with incorporated e.g. pigments in order to modify the light spectrum which enters the greenhouse. In this way, photosynthesis and photomorphogenesis and thereby the growth of the plants can be affected. Following some references from the literature for films and fluid roofs are presented.

2.1.1. Photoselective plastic films

The growth, yield and quality of the strawberry cv. “Elsanta” were studied experimentally by Fletcher et al. [17]. Greenhouses covered with different photoselective films were characterized for a range of R/FR ratios and PAR transmissions. The results showed marketable yield per plant was 51% greater under the film with the highest light transmission (control) compared with the lower light transmission films while cropping duration was longer under films with high R/FR. Also plants under high R/FR were more compact compared to plants grown under low R/FR.

Photoselective plastic films with FR light intercepting dyes were tested by Li et al. [18]. A photoselective film with a R/FR ratio of 2.2 (which corresponds to 75% light transmission) caused about 20% height reduction in chrysanthemum and 30% height reduction in bell pepper after 4 weeks of treatment. The use of greenhouse films with FR light absorbing dyes was proved to be as effective as chemical growth regulators or $CuSO_4$ filters in controlling plant height of chrysanthemums and bell pepper seedlings.

Wilson and Rajapakse [19] tested plant response to photoselective plastic films with varying spectral transmission properties by using lisianthus (*Eustoma grandiflorum*) “Florida Pink”, “Florida Blue” and “Florida Sky Blue”. Films YXE-10 (far red absorbing) and SXE-4 (red light absorbing) were investigated. Selective reduction of FR by using the YXE-10 FR-absorbing film reduced the height of lisianthus by 10% (“Florida Blue”) and internode length by 10% and 19% (“Florida Pink” and “Florida Sky Blue”, respectively) without affecting the development of flowers or flower quality. The height reduction of lisianthus cultivars was less than that of other crops which have been previously tested.

Sub-tropical perennials response to photoselective plastic films with varying spectral distribution properties was tested using three sub-tropical perennials: golden shrimp plant (*Pachystachys lutea*), Persian shield (*Strobilanthes dyerianus*) and cat whiskers (*Orthosiphon stamineus*) by Wilson and Rajapakse [20]. Films YXE-10 (FR light-absorbing) and SXE-4 (Red light-absorbing) were used. Light transmitted through YXE-10 films reduced plant height of golden shrimp and cat whiskers by 10% and 20%, respectively. Light transmitted through SXE-4 films increased plant height by 9% for golden shrimp but did not significantly increase stem length of Persian shield and cat whisker species. Chlorophyll, leaf area and mean days to flower generally were not affected by the photoselective films; except cat whisker plants grown under YXE-10 films (had reduced leaf area compared with plants grown under SXE-4 or control films). Comparing with the control film, light transmitted through YXE-10 films reduced leaf dry weight by 22–31% and stem dry weight by 19–28%, depending on the plant species. Root dry weight was not affected by the spectral films.

Khattak and Pearson [21] studied light quality (R/FR, B/R and B/FR ratios) and temperature effects on antirrhinum growth and development. Three different temperatures 19, 24 and 27 °C (in glasshouses) and five different color filters (“Red absorbing”, “Blue absorbing”, “Blue and Red absorbing” and two “partially Blue absorbing” materials) were tested, with one clear polythene as a control. In order to predict the effects of different spectral qualities and temperature, simple models were developed from data on plant height, internode length and time to flowering. These models were used to simulate the potential benefits of spectral filters and temperature in the manipulation of growth control and flowering in antirrhinum. The results showed clearly that spectral quality had effect on the growth and development of antirrhinum. There was a strong effect of blue light on plant height confirming the presence of a photoreceptor, acting in the blue region of the spectrum. Significant reductions were found in the plant height with the increase in blue transmission; however, the phytochrome photoequilibrium did not appear to have any effect on plant height. On the other hand, plants height and internode length increased as the temperature increased above 19 °C.

Oyaert et al. [22] tested several spectral filters *Dendranthema × grandiflorum* “White Reagan” (*Chrysanthemum morifolium*), as an alternative for chemical growth regulation. Four colored filters were tested: three polyethylene (PE) films containing a blue absorption pigment in different concentrations ($1 \pm 3\%$); a fourth colored filter consisted of a mica film with a vaporized coating of several metaloxide layers, resulting in a transparent film with interference effect. Due to the fact that the light transmittance was different for each colored filter, four different control filters were provided. These control filters consisted of several layers of neutral shading cloths, to ensure equal photosynthetic photon flux densities (PPFD) as under the corresponding colored film. In Fig. 1 the spectral distribution of the transmission spectral of three blue PE films and a vaporized mica film are illustrated. The blue PE films had B/R ratios ranging from 6.2 to 85.5 with increasing pigment concentration and R/FR$_n$ ratio between 0.43 and 1.45. The vaporized film had a relative low B/R ratio (1.41) and a high R/FR$_n$ ratio (2.06) while the B/R and R/FR$_n$ ratios of the control filters were$\approx$1 (where the indicator n=narrow band width). The inhibition of stem elongation increased with increasing pigment concentration under the blue PE films, with maximum growth reduction 22% compared to the control. The blue filters resulted in a lower number of auxiliary shoots, smaller leaf area and lower total dry weight than the control filters. The vaporized film was characterized by the highest light transmission percentage; resulted in a relatively small growth reduction compared to the corresponding control. The positive effects on plant quality are most probably due to the high transmission capacity of this vaporized film, compared to the blue PE films. In terms of the dry matter partitioning, all blue films reduced total plant dry weight and percentage dry weight, while this was not the case under the vaporized film. Furthermore, all the control films were characterized by a ratio between stem and leaf dry weight of

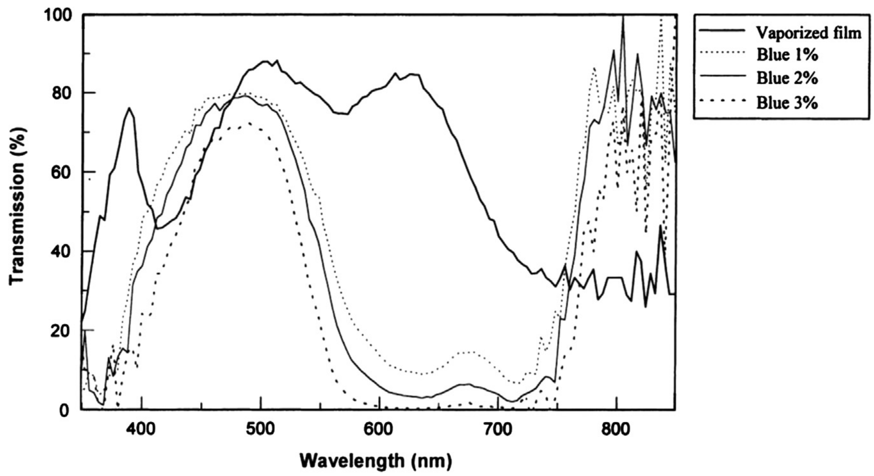

Fig. 1. Spectral distribution of the transmission spectra of three blue polyethylene (PE) films and a vaporized mica film, measured under standard circumstances [22].

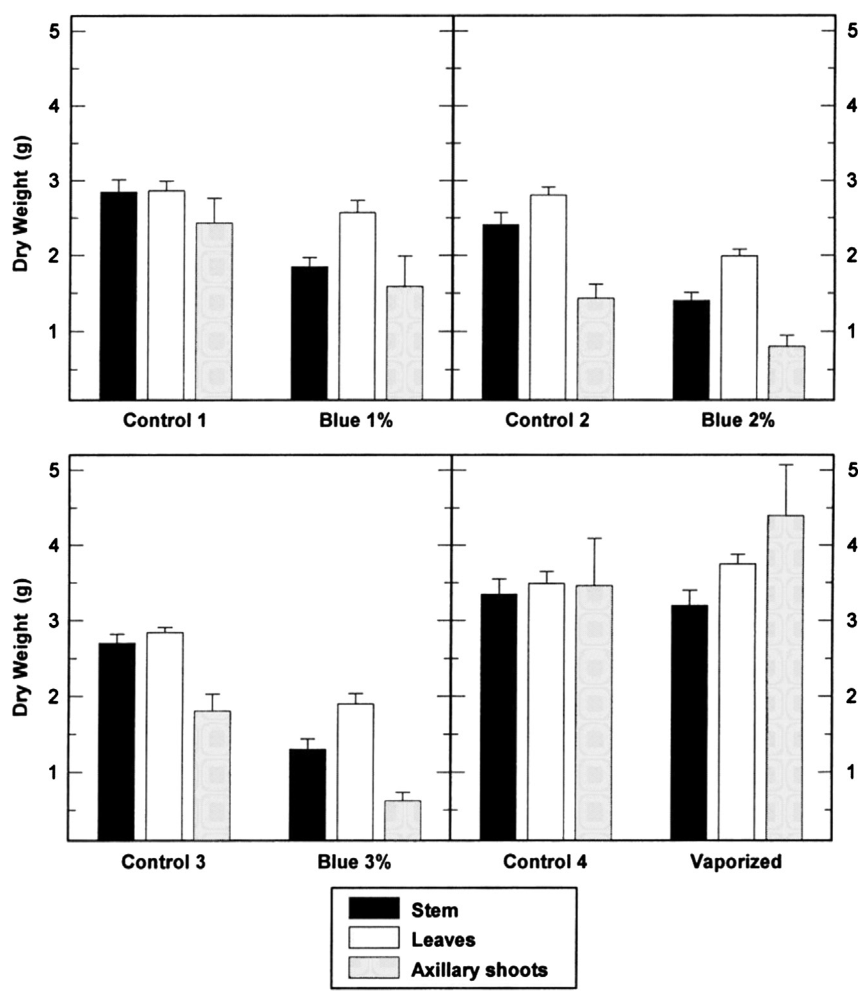

Fig. 2. Effect of four spectral filters on dry weight partitioning of *Dendranthema × grandiflorum* "White Reagan" compared to their corresponding controls [22].

approximately 1:1 (Fig. 2), while under all the colored films relatively more dry weight was stored in the leaves and less in the stems.

Van Haeringen et al. [23] studied phthalocyanine derivatives which were prepared and incorporated into polymer films in order to be used as spectral filters for the modification of plants growth. These spectral filters were designed specifically for the control of plant growth *via* modification of the activity of phytochrome. The unusual absorption characteristics of phthalocyanines, notably the narrow absorption band in the visible region of the electromagnetic spectrum allowed the selective filtering of wavelengths necessary for excitation of either of the two isomeric phytochrome species. The resulting change in the photostationary state for the phytochrome had a marked effect on the growth characteristics of

chrysanthemums and antirrhinums. Chrysanthemums (short-day plants) were grown under a FR-absorbing film and showed a reduction in height (≈14%) and inter-nodal length compared to those grown under a red-absorbing film or a control with no absorption in the visible part of the spectrum; leaf number and time to flowering were not affected by the presence of the spectral filter. Antirrhinums (long-day plants) showed both a reduction in height and a substantial increase in the leaf area (70%) of the plants grown under the FR-absorbing film, although flowering was delayed.

Kleemann [24] studied the effect of FR filters on lettuce quality. The color of the plants grown under FR filter was beautiful light green compared to plants grown in control, which were yellowish, darker green. Under FR filter plants tasted less bitter (compared to plants in the control). Spectral filter affected also leaf orientation. Lettuce leaf position of the control plants was more upright compared to the plants grown under a FR absorbing film. Moreover, the incidence of tip-burned leaves decreased under FR filter. On the other hand, the yield was not significantly different; calcium content was significantly higher under FR filter; and plants grown under FR filter contained less dry matter and chlorophyll.

Magnani et al. [25] studied the impact of sunlight spectrum modification on yield and quality of ready-to-use lettuce and rocket salad, grown on a floating system. Low-density polyethylene (LDPE) films (Colorless, Yellow and Red) were tested during periods with different daylength. The results revealed that the photoselective films had positive effect on dry matter percentage for rocket salad and lettuce, while the fresh weight presented only a slight difference. However, the photoselective films increased the nitrates content. Regarding antioxidant capacity, rocket salad showed an increase (around 40%) in plants grown under the photoselective films. Furthermore, chlorophyll and carotenoid content was little influenced by the optical properties of the materials.

On the other hand, the use of plastic films to cover orchards is important because ripening time can be accelerated or delayed based on the market demand while fruit quality (color, sugar content etc.) can be improved. However, tree cultivation in greenhouses means problems with the control of plant height but this problem could be solved by using growth regulators along e.g. with modifications of the radiation which enters the greenhouse interior space. In the literature there is a study about the influence of innovative photoselective and photoluminescent greenhouse plastic films for the modification of the spectral distribution of the transmitted solar radiation, on the growth of cherry and peach trees [26]. Several claddings were examined: three photoluminescent films, named RED, BLUE and RED-BLUE, created by adding masterbatches which absorb UV and retransmit it in the wavelength band of the red, blue and red-blue radiation, respectively (further anti-UV stabilizers were not added to these films), etc. The annual growth (percentage of shoots length increase) in comparison with the open field (increase set to 100%) for the cherry and peach trees was investigated. The photoselective GREEN4% film (R/FR = 0.93) significantly enhanced the growth of the cherry and the peach trees in comparison to the trees cultivated under the other greenhouse films. The RED film also induced significant shoot length increase in the peach trees. The plants grown under the BLUE film showed lower values of the annual increase of the shoots. Conclusively, the experimental field tests of that study revealed that: (1) it is possible to alter the quality of the solar radiation under covering plastic films and affect photomorphogenesis of trees for potential economic benefit/facilitation of the cultivation, (2) the modifications of the solar spectral distribution mainly in the R and FR wavelength band influenced the shooting growth of the peach and the cherry trees [26].

Nishimura et al. [27] conducted a study about the effect of a spectrum conversion covering films on cucumber soilless culture. They developed a spectrum conversion covering film which changed light from the low active region (green light) for photosynthesis to the effective region (red light). Experiments on nursery stage vegetables were conducted. For the cucumber crops, the quantity of photosynthesis was greatly influenced since the growth rate of the plant and the fruit is fast. The results revealed that the total yield, the growth as well as the fruit dry matter rate of the cucumbers grown under the spectrum conversion covering film were greater than for the cucumbers grown under the non-conversion film; however, there was no difference in fruit length, level of bent fruit and average fruit weight between the two films. Furthermore, P concentration in the 10th leaf and in the fruit under the spectrum conversion covering film was higher than under the non-conversion film. In addition, the concentrations of other mineral elements under the spectrum conversion covering film tended to be higher than under the non-conversion film. It should be noted that the light transmission characteristics of the covering conversion film did not change after 42 months. In conclusion, the spectrum conversion covering film was proved to be effective for stable cucumber production because of the high yield and the good nutrient absorption.

2.1.2. Fluid roofs

Plant morphogenesis can also be controlled by means of colored solutions in a fluid-roof system. In the literature there are some studies about this type of systems.

Mortensen and Moe [28] studied the effect of different light qualities on plant growth by means of a fluid-roof system with different colored solutions. Removing most of the FR light resulted in reduced shoot length and compact plants compared to the control ones. Reducing blue light component of the daylight led to shoot elongation. Removing the twilight at sunset gave no or only small effects on tomato and chrysanthemum growth. Along with plants morphogenesis control by the light quality, the fluid-roof system could also control the temperature without ventilation of the greenhouse.

McMahon and Kelly [29] investigated the influence of $CuSO_4$ filters on flowering of *Chrysanthemum* cv. "Spears" which was grown under solar filters filled with $CuSO_4$ in solution which absorbs FR, or water, which does not absorb FR. The plants were exposed to marginally long natural photoperiods, artificially long photoperiods, or artificially short photoperiods. Chrysanthemum grown under $CuSO_4$ filters had reduced internode length and plant height compared to plants grown under water filters, regardless of photoperiod. Plants grown under water- or $CuSO_4$-filled filters which received artificial short days, flowered 7 days ahead of the plants grown in natural, marginally long photoperiods under $CuSO_4$ filters and 17 days ahead of the plants grown under water filters and receiving natural, marginally long photoperiods. Regarding the number of nodes, it was the same for the plants grown in short and marginally long days under $CuSO_4$ filters and in short days under water filters, which means that flower induction occurred simultaneously in these treatments. The development of additional nodes on plants under water-filled filters and receiving natural long-days indicated that floral induction was delayed. Cool white fluorescent light night break prevented or delayed flowering of plants grown under water- and $CuSO_4$-filled filters during natural short days. Thus, standard practices of photoperiodic control could be used to time Chrysanthemum cv. "Spears" grown under $CuSO_4$ filters for pot mum production. At this point it should be noted that potted chrysanthemums are a floriculture crop of great economic significance and the esthetic appeal of these plants determines their market value. Full, bushy, compact plants in proportion to the container have the greatest value.

2.1.3. Critical issues

Conclusively, this type of cladding provides advantages such as the increase of plants yield and the acceleration or delaying of plants growth. Nevertheless, before the adoption of these covers e.g. for a commercial greenhouse, factors such as the cost of the pigments which are incorporated into the cladding as well as (for the case of the fluid roofs) the integrability of these systems into greenhouse roof, should be addressed.

2.2. Fluorescent solar concentrators (FSC)

2.2.1. Several technologies

The operation of FSCs, is based on the following principle: one or more high quantum yield species are dissolved in a rigid, highly transparent medium of high refractive index. The solar photons which enter the plate are absorbed by the luminescent species and reemitted in random directions. Based on Snell's law, a large fraction of the emitted photons will be trapped within the plate and transported by total internal reflections to the edge of the plate. In Fig. 3, the above mentioned phenomenon can be seen as well as the possibility of combining FSCs with PVs. In this way, the trapped photons are transferred to the edges where are converted into electricity by the appropriate PV cells. This possibility is an important issue of FSCs and is mentioned in Ref. [8]. Hammam et al. [8] evaluated the performance of thin-film FSCs for greenhouse applications. In the frame of that study, transparent Polymethylmethacrylate (PMMA) films impregnated by a fluorescent organic laser dye of red emission spectra were prepared. Due to the small film thickness, a large fraction of the emitted photons was transmitted. It should be noted that dye concentration could be optimized in order to match the spectral sensitivity for the photosynthesis of red algae and higher plants. The dye absorbed the green–yellow wavelength band which is not utilized by the chlorophylls. Regarding the effect of dye concentration on the fluorescence spectra of the investigated films, it was shown that a maximum in the intensity was obtained for the concentration 50 ppm and the maximum red shift (623 nm) for 100 ppm. All the samples exhibited high transmission values with a maximum around the concentration of 50 ppm due to its excellent fluorescence properties, thus most of the effective red light can be transmitted promoting plants growth. In terms of the photostability, PMMA is a good matrix for organic laser dyes since it can protect the dye from thermal and photo-degradation. Concerning, the temperature effect, after cooling the sample to room temperature the fluorescence intensity retained to its initial value which means that the film exhibited excellent weathering durability in different climates (the study covered wide range of atmospheric temperatures). Conclusively, the tested films were found to be promising photoselective films and could increase the irradiance level for photosynthesis in greenhouses as well as in growing rooms in which plants such as red algae with great economical importance (in food, pharmaceutical, cosmetic, etc. applications) are grown [8].

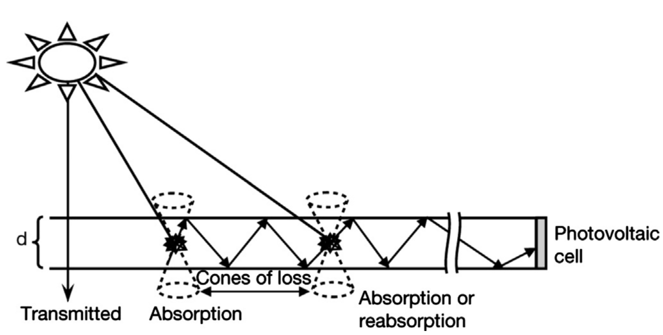

Fig. 3. Schematic of a Fluorescent Solar Concentrator (FSC) combined with a Photovoltaic (PV) solar cell [8].

Novoplansky et al. [30] conducted a study about the increasing plant productivity by changing the solar spectrum. Greenhouse plastic covers were prepared by incorporating fluorescent dyes into PE sheets made by extrusion. These dyes converted light from the green part of the spectrum into red light. The use of these greenhouse covers increased the weight of the tomato fruit yield by 19.6% and the number of the flowering branches on rose bushes by 26.7% compared with the sheets without the dye. The increased yield was primarily due to a morphogenetic response of the plants to the spectral change of the light, which enhanced the development of the desired organs while it is possible that there was an increased rate of photosynthesis.

Pearson et al. [31] investigated the radiation transmission and fluorescence of several greenhouse gladding materials. PAR transmission (wavelength from 400 to 700 nm) was determined for each of the materials in three ways: by weighting the spectral components according to either the energy or the number of photons or the photosynthetic efficiency of photons. It should be mentioned that weighting according to the photosynthetic efficiency generally produced slightly higher values of film transmission, compared to the other methods. The highest PAR transmission (94.2%) (determined on the basis of photosynthetic efficiency) was recorded on a PE-based film containing a fluorescent additive. There was a large variation in the degree to which films scattered the light: polycarbonate scattered 7.2% of the incident irradiation; a diffuse PE scattered 86.6%. In all the films, the percentage of scattered radiation decreased with wavelength. A number of fluorescent films were examined and the most efficient was one which absorbed UV and re-emitted it between 400 and 480 nm. Even with this film only 16% of the absorbed UV was fluoresced in a downwards direction. Drop-wise condensation on the surface of a cladding reduced solar transmission by 13%, for all the measured angles of solar incidence. The quantity of water on the film surface had little effect on this reduction. However, very little reduction in transmission (3%) was recorded on cladding which had anti-fogging agents and produced film-wise condensation. The results of that work showed the importance of considering all solar spectrum regions when designing and evaluating greenhouse cladding materials. The efficacy of using fluorescent compounds to convert PAR radiation of short “blue” wavelengths to more efficient PAR at “red” wavelengths must be questioned; because fluorescence is an inefficient process and also a large part of the radiation will be fluoresced back to space. Thus, it is unlikely that any theoretical gain through increased photosynthetic efficiency will outweigh the loss due to the PAR fluorescence absorption at short wavebands. However, fluorescence of non-photosynthetically active UV radiation to a PAR waveband is desirable because it can increase the PAR incident on the crops and also plants diseases may be reduced.

Hemming et al. [32] studied the effect of different fluorescent films on the production and quality of strawberry fruits and several flowers. Strawberry plants were grown in small tunnels covered with films which contained blue fluorescent pigments in different concentrations which increased total light transmission and influenced light quality (more blue light). Blue fluorescent films led to higher yield, higher number of fruits and a slightly higher mean fruit size for the strawberries. The differences in fruit quality were small. On the other hand, blue fluorescent films gave a 4 days earlier yield to *Alchemilla* and a 2 days earlier yield to *Virburnum*. Moreover, flower quality of *Alchemilla* was improved. This could be attributed to higher day temperatures and lower humidity caused by a higher light transmission of the film. The same film caused a 5 days earlier yield to *Celosia* and at the same time improved flower quality. The results revealed that the

developed greenhouse films containing blue fluorescent pigments showed good potential to: (1) positively affect growth and development of strawberry "Elsanta" and (2) lead to earlier flowering of perennials in spring and improve flower quality under Dutch climate.

González et al. [33] investigated the efficiency of new fluorescent plastic films, especially those including additives which work as green to red light converters. Two field tests were carried out in Spain, for strawberries under a low tunnel and cucumbers under a Kyoto type tunnel-greenhouse. UV-absorbing fluorescent orange coextruded three-layer and fluorescent magenta coextruded three-layer films were tested. An UV-non absorbing white coextruded three layer film was used as control film and all the compared films were of 75 μm thick. The yield, growth and development characteristics of strawberries and cucumbers were quite irregular and independent of the plastic film used. The control film showed the greatest PAR and UV transmission. The highest number of thrips population was observed in the tunnel-greenhouses covered with the control film. On the other hand, the minimum number of thrips population was observed in UV-absorbing fluorescent magenta coextruded three-layer film. The fluorescent films showed lower PAR values throughout the growing period in comparison with the control film.

Hemming et al. [34] investigated the effect of new developed fluorescent greenhouse films on the growth of *Fragaria* × *ananassa* "Elsanta". In order to optimize light quality and quantity for plant growth, several photoselective greenhouse covering materials which contained different fluorescent pigments (Blue, Red1, Red2, Red3) in different concentrations, were developed. Excitation of all the fluorescent pigments took place at around 365 nm. Blue pigments showed fluorescence between 410 and 480 nm, Red1 and Red2 pigments between 610 and 630 nm and Red3 pigment between 600 and 690 nm; also major parts of the blue and green spectrum were absorbed. Fluorescence effects of the plastic film prototypes were rising with increasing pigment concentration; however, fluorescent effects were small. Blue pigments resulted in 1–3% increase of the total PAR transmission while Red pigments reduced PAR transmission. Only pigment Red3 increased the R/FR ratio with 10%. Blue fluorescent films seemed to be favorable for strawberry fruit production and this could be attributed to the higher PAR transmission of the films or to the light quality effect. Blue fluorescent films caused 11% increase of the strawberry production, mainly because of an increase of fruits number. Red3 fluorescent film significantly delayed fruit production. The total yield under Red3 film was 10% lower than under the Reference one due to the lower PAR transmission and the increased R/FR ratio. Fruit color was slightly influenced by the different film prototypes. Fruits grown under Blue fluorescent films were slightly brighter but more saturated than fruits grown under the Reference one. Fruits grown under Blue films were found to be slightly more acid than fruits grown under the Reference one while fruits grown under the Red films were less acid. Conclusively, the greenhouse films containing blue fluorescent pigments showed good potential to positively affect the growth and development of *Fragaria* × *ananassa* "Elsanta", while red fluorescent films seemed to be less promising.

Minich et al. [35] conducted a study about the vital activity of *Lactuca sativa* and soil microorganisms under fluorescent films. The productivity of *L. sativa*, variety Moskovsky parnikovy growing in protected cultivation under fluorescent film luminescent with a maximum of 615 nm was examined. The change of the conditions of plant cultivation by fluorescent film, promoted accelerated growth, development and productivity improvement of *L. sativa* in comparison to the plants growing under unmodified film.

2.2.2. Critical issues

It should be mentioned that when considering the feasibility of FSC covers, factors such as the cost of the pigments which are added in the claddings should be taken into consideration. On the other hand, the combination of FSC with PVs is an interesting option for the "utilization" of the trapped photons with parallel production of electricity [8].

2.3. Passive optical means

Following are presented some studies about passive optical means. These systems are very simple, have few or no mechanical parts and require no mechanical systems and minimal maintenance.

2.3.1. Several technologies

Edmonds and Pearce [36] conducted a study about the illumination enhancement by installing laser-cut panels (LCP) as double-glazing on the south-facing roof of greenhouses in high latitude countries. The enhanced illuminance in a greenhouse, averaged over a day, as a function of latitude and sky turbidity was calculated. The results revealed that, relative to single glazed conventional greenhouses, a daily average enhancement exceeding 80% can be achieved at latitudes of 50° and higher in winter under clear sky conditions. Experimental verification of predictions was based on measurements in scale-model greenhouses. In Fig. 4, the relative areas of illuminance enhancement available by the use of a LCP glazing on the roof of a greenhouse are illustrated.

On the other hand, Critten [37] investigated the light enhancement of a greenhouse by using E–W aligned long prismatic arrays at high latitude. A computer model of light enhancement by prismatic reflection or refraction of sunlight was developed, tested and showed reliable predictions. Model results for prisms (without surface curvatures) proved that only the directly transmitted northerly and single reflected southerly sunlight produced useful irradiance. The addition of curvature to the prism and rear surfaces spread out the angular distribution of the light from the array, performing a useful function.

Moreover, Critten [4] conducted an investigation about the use of reflectors in venetian blinds to enhance irradiance in greenhouses. The results revealed that experimentally a standard venetian blind (3 m long by 2 m deep) with reflecting surfaces on the concave side of the louvres, was capable to produce an average light gain about 7% across a conventional single-span house under winter sunlight conditions at midday, though the

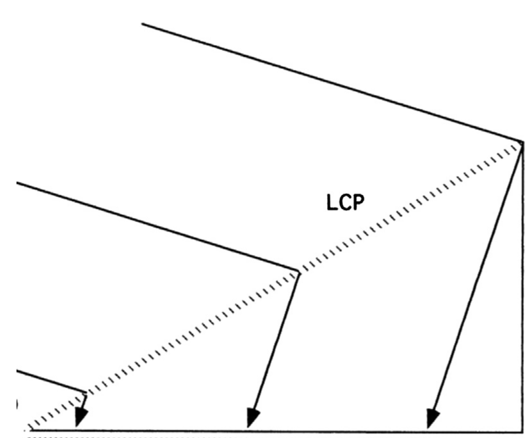

Fig. 4. The relative areas of illuminance enhancement by the use of a laser-cut panel (LCP) glazing on the roof of a greenhouse [36].

gain was all in the southern half of the house with a small loss in the northern half.

2.3.2. Critical issues

The passive optical means refer mainly to studies several years ago. This could be attributed to the fact that these systems did not show satisfied efficiencies or cost effectiveness and these factors are basic for the commercial applicability of a proposed system. On the other hand, the practical applicability of these claddings should be addressed.

2.4. Roofs with desalination systems

Another type of greenhouse cladding is the desalination roof. In the literature there are only a few studies about this type of covers. Following some works about this specific type of cladding are presented.

2.4.1. Several technologies

Chaibi [10] studied greenhouse systems with integrated water desalination for arid areas, based on solar energy technologies. In Fig. 5, the principle of a water desalination system integrated into a greenhouse roof, is illustrated [38]. Low quality irrigation water e.g. with salts, may reduce crop yield and also may have negative effects to the environment. The analysis of such a system requires complex technical and biological approaches. The results of Chaibi [10] revealed that daytime climate variations had a less peaky pattern around noon which resulted in lower water demand (positive for the crop conditions). In terms of the optical performance of the system, the absorber material chosen was a single glass coated with solar protection film with a total light absorptance around 56%. The spectral PAR and NIR transmission for the complete roof was simulated with high accuracy. A small transmission increase of about 2%, in the interval between 300 and 700 nm with water layer compared to the case without water on the absorber, was observed. However, a transmission decrease of about 5% was noticed for the NIR wavelength range. The use of absorber glasses with higher selectivity could decrease the yield reduction from 25% for conventional glass types with 50% of the absorption in the NIR spectrum down to 15% and even to 3% for glasses with NIR absorptance proportion of 70% and 90%, respectively. Regarding the economic analysis of the proposed system, fresh water cost was calculated to be about 7$/m^3 [10].

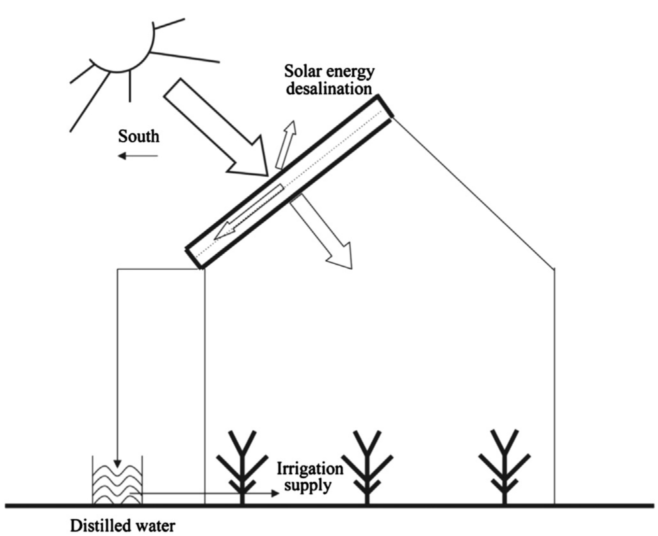

Fig. 5. The principle of a water desalination system integrated into a greenhouse roof [38].

In the context of that concept, Chaibi and Jilar [38,39] studied various design cases of greenhouse systems with integrated water desalination, including crop cultivation examples. The studies included a simulation model for the thermal and optical performance of the actual system concept, combined with a lettuce growth model as well as laboratory experiments. The model predicted PAR accurately. The total PAR transmission was about 2% higher with water flow compared to a case without water. The model also described accurately NIR transmission. The total transmission was calculated to be about 5% lower with water compared to the case without water. The simulated lettuce yield reduction was about 25% (for a desalination case with the capacity to cover the water demand which corresponds to a lettuce crop) in relation to a conventional greenhouse case with single glassed roof. The yield problem could be solved with more light selective glass materials (NIR-absorption). Electrochromic glasses with dynamic absorptance control could be an interesting future prospect. In this way, crop yields could be improved and the seasonal storage demand could be eliminated [38,39].

2.4.2. Critical issues

For the case of desalination roofs the economic feasibility of the system is a crucial factor and should be carefully examined. Another important aspect has to do with the extent of the possible reduction of the incoming solar radiation. The above mentioned aspects are critical and should be taken into account.

2.5. Anti-condensation (anti-drip) claddings

The droplets which are formed at the inside surface of the greenhouse films (due to the condensation of the water) can have negative effects on plant growth and quality. These negative effects are mainly related with the reduction of light transmission as well as with the increase of certain diseases. Thus, several anti-drip claddings have been developed. These films may contain specific additives that eliminate droplets and form instead a continuous thin layer of water which can run down through the sides.

2.5.1. Several technologies

Katsoulas et al. [40] investigated the effects of anti-drip PE covering films on microclimate and crop production. Techniques based on anti-drip (AD) and anti-fog (AF) cover materials were examined. The effects of two AD–PE cover materials on greenhouse microclimate/growth/production of a hydroponic cucumber and tomato crop were experimentally studied. A standard PE film covered one of the three greenhouses (C-PE). The other two greenhouses were covered: the first by a PE film with anti-drip (AD) and anti-fog (AF) properties (AD+AF – PE) and the second one by a PE film with AD properties (AD–PE). The results revealed that the relative humidity levels were much higher in the AD–PE covered greenhouse. Moreover, the temperature difference between the cover material and the dew point air temperature was more negative under the same greenhouse, leading in higher condensation rates over the PE film. The crop development and production was similar in the three greenhouses. Nevertheless, in order to control fungus development, the greenhouses covered by the C–PE and the AD–PE film needed about double fungicide applications than the greenhouse covered by the AD+AF–PE film.

Pollet and Pieters [12] determined experimentally the angular transmittances over the PAR range of two types of glass (single glass (SG) and low emissivity glass (LEG)) and three types of plastic films (LDPE, anti-drop condensation PE (ADCPE) and photoselective diffusive PE (DPE)). The measurements were

performed on dry as well as on condensate covered materials. Based on the angular measurements, the transmittance of diffuse PAR incident on a 25° inclined slab was determined. In terms of the dry state, it was found that the PAR transmittance decreased with increasing the photoselectivity of the materials. For the case "covered with condensate", the PAR transmittance of the glass plates was only reduced at incidence angles higher than 15° by at most 20% on a relative scale, while the transmittance of non-anti-drop condensation films was especially reduced at small angles of incidence by at most 25%. Due to the presence of anti-drop condensation agents to a plastic film, the PAR transmittance of the film was not affected by the condensate and therefore showed the highest PAR transmittance in the wet state. Furthermore, for the photoselective cladding materials, the spectral dependency of the transmittance was only slightly changed by the condensate. In general, for small angles of incidence, no significant transmittance differences between the dry and the wet state of both glass products were found while at higher incidence angles condensate resulted in transmittance decrease. Among all materials investigated, the wet ADCPE film had the highest transmittance in the wet state. It should be noted that the PAR transmittance of ADCPE was remarkably high when compared with the other wet plastic films for all the angles of incidence. Fig. 6 illustrates that in contrast to the transmittances for the dry state, ADCPE showed the highest hemispherical–hemispherical transmittance value for the wet state, since that was the only material whose transmittance was not reduced by the condensate (on the contrary, a small transmittance increase of 1% was observed). When compared with the wet ADCPE, the transmittance of the wet DPE was 30% lower. Finally, it should be mentioned that the results are valid for newly manufactured cladding materials which are not affected by ageing and that run-off of condensate did not occur during the transmittance measurements [12].

Pieters and Deltour [41] simulated yearly auxiliary heating requirements for four greenhouses (tomato crop), covered with different cladding materials. The simulations were carried out both taking into consideration and neglecting condensation/evaporation phenomena inside the greenhouse. The results showed that under a temperate maritime climate, the values for the heating requirements obtained by the model without allowing for condensation were underestimated by about 15% for glasshouses and overestimated by about 20% for a PE-covered greenhouse. Condensation on greenhouse cover was shown to be the far most important sink for water vapor for the inside air during night. The evaporation mass fluxes from the cover were found to be very low and almost the same for all claddings, condensation fluxes were demonstrated to be much higher and much more dependent on the cladding material. Neglecting of the condensation was found to have almost no effect on the simulated inside air temperature of an active greenhouse, i.e. a greenhouse whose inside climate is controlled actively by heating and ventilating, while it led to overestimating of the relative humidity by about 10%, the errors were somewhat smaller for greenhouses with low emissivity cladding during daytime. It also resulted in overestimating or underestimating of the vegetation temperature, according to the far-infrared radiation properties of the cladding material (low transmittances gave rise to overestimating).

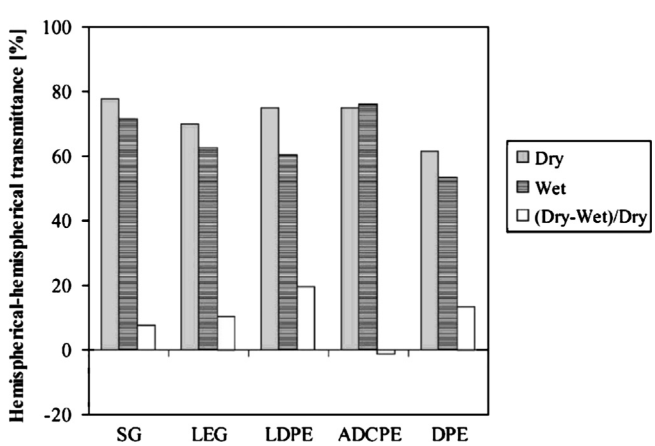

Fig. 6. Hemispherical–hemispherical transmittance values for a 25° inclined slab of several claddings: single glass (SG), low emissivity glass (LEG), low density polyethylene (LDPE), anti-drop condensation polyethylene (ADCPE) and photoselective diffusive polyethylene (DPE); in the dry and the wet state and the relative effect of the condensate under standard overcast sky conditions [12].

Cemek and Demir [42] investigated eight model pitched roof greenhouses in order to study the optical transmission of agricultural plastic films. Light transmissions in terms of time and condensation characteristics were determined in the experimental greenhouses covered with: UV stabilized PE (UV+PE), IR absorber PE (IR+PE), PE with no additives (PE) and double layer PE films (D-Poly). A comparison of light transmission of the films over a period of 3 months revealed that all the films in the dry state had higher transmission than in the wet state. Light transmission of D-Poly was the lowest while that of PE was the highest. The average loss in transmission due to dirt was approximately 9–15%. Drop size and water condensation were highest in IR+PE followed by UV+PE and PE.

Furthermore, Pearson et al. [43] studied radiation transmission of greenhouse gladding materials. The results showed that drop-wise condensation on a cladding surface reduced the solar transmission by 13%, for all the measured angles of solar incidence while water quantity on the film surface had little effect on this reduction. On the other hand, very little reduction in transmission (3%) was recorded on a cladding which had anti-fogging agents and produced film-wise condensation.

In addition, Pieters et al. [44] investigated the angular dependence of forward scattering induced by condensate on greenhouse cladding materials in order to determine the extent at which the radiant scattering pattern was determined by the radiant incidence angle on the cladding surface. The forward scattering properties of four cladding materials: LDPE, anti-drop condensation PE (ADCPE), diffusive PE (DPE), single glass (SG) were measured in the dry state and when covered with condensate at several incidence angles (0°, 15° and 30°). In the dry state, SG behaved as a quasi-non-diffusive material in contrast to the three plastic films which scattered the radiation due to their surface roughness, bulk heterogeneities or the addition of diffusive agents. Except for the ADCPE, the forward scattering of the materials was broadened by the presence of condensate. For these cladding materials, the scattering pattern shifted towards the normal to the cover with increasing incidence angle.

2.5.2. Critical issues

Certainly, the management of high humidity levels during the cold months is of great importance in order to achieve better yield and quality of the greenhouse products, without fungal diseases. Anti-drip films, provided that they are used properly, can offer advantages such as more light in the greenhouse interior space, higher crop yield, better crop quality (and thus higher commercial value), reduction of diseases (and therefore reduced needs for pesticides). However, at this point it should be noted that these films are mainly recommended for greenhouses which are well ventilated (and/or heated) with adequate inclination of their roofs. On the other hand, the anti-drip effect is reduced as time passes because it is possible the additives to be washed out by the run-off water. Furthermore, in some cases of greenhouses with anti-drip

films, fog maybe created (e.g. during sun-set) in the greenhouse interior space. At this contingency, it is desirable to ventilate (and/or heat) the greenhouse immediately in order to remove the fog. Another solution is the use of anti-drip films with special anti-fog functions. However, also this solution does not necessarily implies effectiveness since it is associated with complex mechanisms. In the study of Geoola et al. [45], information about the anti-drop properties of greenhouse cladding materials can be found.

2.6. Claddings which diffuse sunlight

Diffuse light has the ability to penetrate deeper into a plant canopy in comparison to the direct light. Depending on factors such as the seasonal variation of solar radiation, the effects on the crop are varying.

2.6.1. Several technologies

Cabrera et al. [46] characterized and analyzed the components of solar radiation under a highly diffusing cover material. Measurements of outside and inside global and diffuse radiation were carried out under a plastic greenhouse. It was shown that the cover diffusive properties can be characterized in situ through sound physically-based parameters. It was highlighted that these parameters were primarily dependent on the diffusive properties of the cover, with a seasonal modulation due to the influence of the beam incidence angle. It was found that the direct-to-diffuse transmittance (τ_{b-d}) was significantly less sensitive to the incidence angle than the direct-to-direct transmittance (τ_{b-b}). Factors such as condensation and dust deposition might have significant non-permanent effects on τ_{b-d} and τ_{b-b}, during some periods of the year. In addition, a straightforward means to obtain a quantitative estimate of the amount of inside diffuse radiation through the relationship (power function) between the greenhouse diffuse ratio (ρ) and the outside diffuse-to-global fraction (f_o) was proposed. Conclusively, the results stressed the significant impact of the cover diffusive properties on inside solar radiation partitioning and the importance to account for these changes in models aimed to estimate the direct/diffuse components, canopy radiation interception and yield in greenhouses.

In terms of rose cultivation, the high energy demand at higher latitudes is caused by the need for artificial light to supplement scarce sun radiation while too high radiation levels reduce flower quality. Therefore shading is widely applied during spring and summer by means of e.g. movable screens or seasonal whitewash. However, the use of diffusing cover materials can improve the uniformity of the vertical light distribution in a crop canopy and has the potential to decrease the energy load on the uppermost crop layer. Thus, this type of claddings could be utilized in the frame of rose cultivation in greenhouses. Experiments about the application of such a cover have been conducted for a rose cultivation (cv. Red Naomi) at the research station of Wageningen UR Greenhouse Horticulture in Bleiswijk, NL, in two compartments. The one of these was covered with diffuse glass with anti-reflection coating with a light transmission of 93% perpendicular and 83% hemispherical and a haze factor of 72%. On the other hand, the reference compartment was covered with standard glass. The results revealed that the effect on greenhouse climate was limited but flower temperature was reduced in the diffuse compartment which had effect on flower quality [47].

In addition, Hemming et al. [13] investigated several diffuse greenhouse covering materials and the results showed that the potential for diffuse covering materials is much higher for semi-arid climates than for marine winter climates. Several light diffusing materials (plastic films, glass, temporal coatings) are available and for the current materials higher haze results in higher light loss. Materials which combine high haze with high hemispherical light transmission should be developed and regular surface structures as well as additional nano-coatings seem to have potentials. The optimal combination of properties has to be found for different climatic regions in order to optimize the performance of the crops.

Jongschaap et al. [48] analyzed by means of simulation models the conversion of direct solar PAR (PARDir) into diffuse (PARDif) and its effects on greenhouse crop production. PARDir can be converted into PARDif by increasing the haze of greenhouse covers with a minimal loss of radiation transmission. A dynamic crop growth model was adopted to quantify the yearly production of tomato, cucumber and sweet pepper cultivations. The results of the model revealed that the conversion of direct radiation to diffuse shifted the vertical distribution of PAR to deeper canopy layers. The total photosynthesis of the top canopy layer was reduced by 0.5%, but photosynthesis per MJ absorbed PAR increased. Deeper canopy layers received and absorbed more PAR, therefore increasing total canopy photosynthesis. If all incoming PARDir was converted to PARDif, photosynthesis increased by 1.5% (winter), 4.0% (summer), 3.4% (fall) for cucumber; 1.5% (winter), 4.3% (summer), 4.2% (fall) for sweet pepper; 1.4% (winter), 3.5% (summer), 2.6% (fall) for tomato. Different reactions between crop types were related to differences in leaf area index evolution in the course of the growing season while about 55% of all the benefits were obtained in summer months, when the amount of PARDir was the greatest and leaf area index (LAI) was sufficiently high. In Fig. 7 the simulated effect of haze (i.e. fraction PARDir that is converted into PARDif) on the yearly photosynthesis increase (%) of a sweet pepper cultivation in comparison with the reference case (haze=0.0) is illustrated.

2.6.2. Critical issues

For the case of claddings which diffuse the light, except of the seasonal variation of solar radiation, crops development is another factor which is related with leaf area index and thus can affect the light distribution in greenhouse interior space. Regarding the choice of the most appropriate level of diffusion (low, medium, high), factors such as the climate of the greenhouse installation area, the crop and the season of growing should be taken into consideration.

2.7. Other types of claddings

Following are presented some other categories of greenhouse covers: double, zig-zag claddings and photoselective nets.

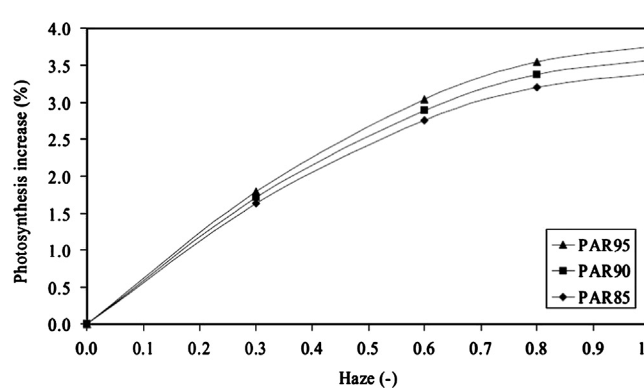

Fig. 7. The simulated effect of haze (i.e. fraction direct PAR that is converted into diffuse PAR) on the yearly photosynthesis increase (%) of a sweet pepper cultivation (for different greenhouse cover transmission factors τ_c: 0.85, 0.90 and 0.95), in comparison with the reference case (haze=0.0) [48].

2.7.1. Double and zig-zag claddings

O'Flaherty and Grant [49] studied the use of double cladding techniques to reduce greenhouse losses. The comparison of the heat consumption of double-clad and single-clad PE configurations over four heating seasons revealed that the double-clad case had substantially lower energy consumption.

Another option for energy savings are plastics with a zigzag double-web structure which combines energy saving with high light transmission. These claddings were investigated by Sonneveld and Swinkels [50] and the results showed that this material combines high light transmittance with good thermal insulation. The energy savings for a greenhouse with a roof of (double) zigzag-sheets are significant. During winter (maximum heating), the momentary energy saving was found to be 45%. The typical year round energy consumption was calculated by means of the simulation program Kaspro for the following cultures: sweet pepper, tomato, pot-plant, chrysanthemum (using climate data for the Netherlands). In Fig. 8 the results for four different cultures are presented. For that covering material a year round energy saving of 20–25% (depending of the culture) was calculated (compared with single glass covering).

On the other hand, Abbouda et al. [51] examined the effect of using double layers of PE cover with air gap on the control of the environment in greenhouse interior space. The effects on the energy transport characteristics and vegetative growth parameters and production of tomato plants under certain climatic conditions were studied and compared with the commonly used double layers (without air gap). The results showed that the greatest values of cooling effect (11.97 °C) and the effectiveness of the evaporative cooling system (75.05%) were achieved inside the greenhouses covered by double layers of PE with 9 cm air gap. In addition, the use of this specific type of cover also led to increase of the vegetative growth rate by 13.1% and yield of fresh tomatoes by 76.13%.

2.7.2. Photoselective nets

Photoselective shade-nettings are a specific category of nets. The photoselective net products have various chromatic additives, light dispersive and reflective elements and screen various spectral components of solar radiation (UV, PAR and beyond) and/or transform direct sunlight into scattered light. By means of several spectral manipulations, desired physiological responses can be achieved. Furthermore, scattering can improve the penetration of the modified light into the inner plant canopy. An additional benefit is the photoselective effect on plant diseases, pests and beneficial insects [14]. Following some studies from the literature are presented.

Control of flowering is important in strawberry production. Takeda et al. [52] conducted a study in order to determine the subsequent growth and flowering response of strawberry plants in the field after transplants were grown under photoselective nets for one month. In the frame of that work, during August, strawberry plug plants were grown under red or blue nets or without shading (control) in a glasshouse. The fall flowering response was determined following transplanting into a plasticulture system in the field. The control plants began flowering in late September and by late November more than 90% of them had bloomed; from October to early January they produced fruits. On the other hand, flowering in plants that were grown under red- or blue-colored shade net did not occur until early January. Conclusively, the use of photoselective shade nets over strawberry plug plants in August resulted in blocking of the light signal which initiates flowering until the netting was removed, thus the initiation of the flower buds until plants were transplanted in the field was delayed.

On the other hand, Shahak et al. [14] conducted a study about the responses of several horticultural crops to photoselective netting. Aspects such as crop performance, pest infestation, the combination of nets with other covering materials were reviewed. In Figs. 9 and 10 some results for bell pepper (*Capsicum annuum*) cultivation are illustrated. This crop is commercially grown at the arid Besor area in Israel under shade nets of 30–40% shading for producing high-quality fruit. Thus, sunburns are avoided and water-saving irrigation is achieved. Shahak et al. [14] compared the traditional black shade nets with the Red, Yellow and Pearl nets in terms of their effect on pepper productivity and quality. The spectra of transmittance of total light, and spectra of scattered (diffused) light under these nets are shown in Fig. 9(a) and (b),

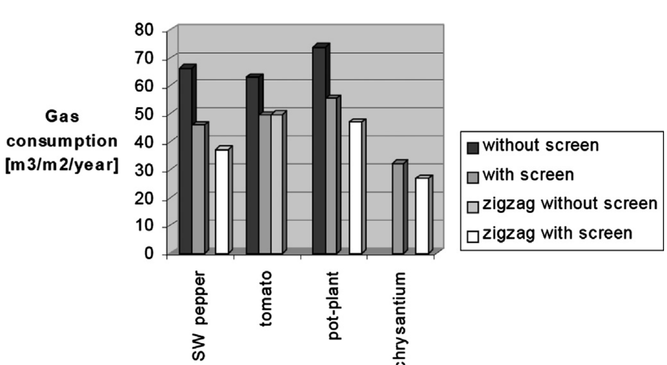

Fig. 8. Calculated results for the gas consumption of a year round, for Dutch climate data and for the cultures: sweet pepper, tomato, pot plant and chrysanthemum [50].

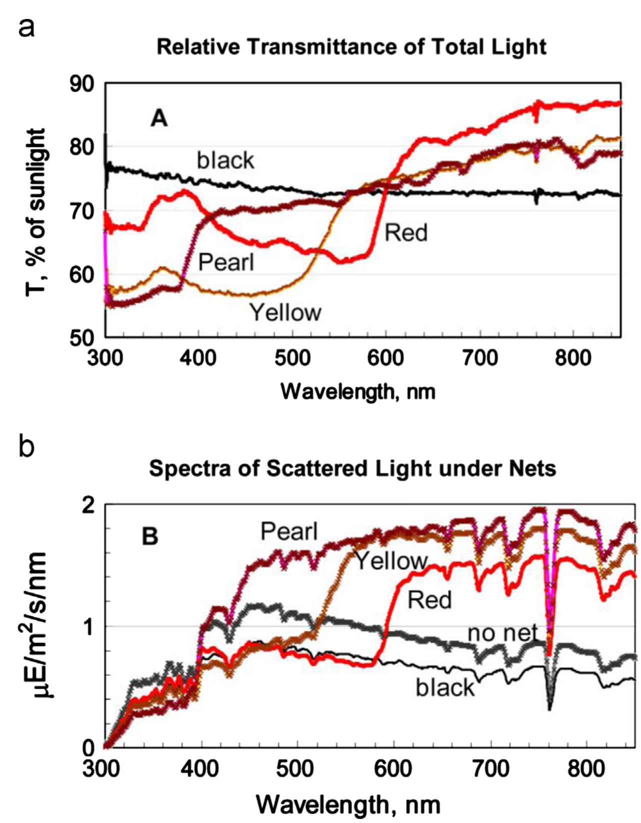

Fig. 9. (a) Spectra of transmittance of total (direct and scattered) light, (b) spectra of the scattered light intensity under the colored nets (transmittance spectra was derived from the spectra of total light under each net divided by the spectrum with no net; total and scattered PAR intensity was 1894 and 295 (no-net), 1379 and 482 (pearl), 1382 and 221 (black) μmol/m^2/s/nm, respectively, measured at mid, clear day on 6/7) [14]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

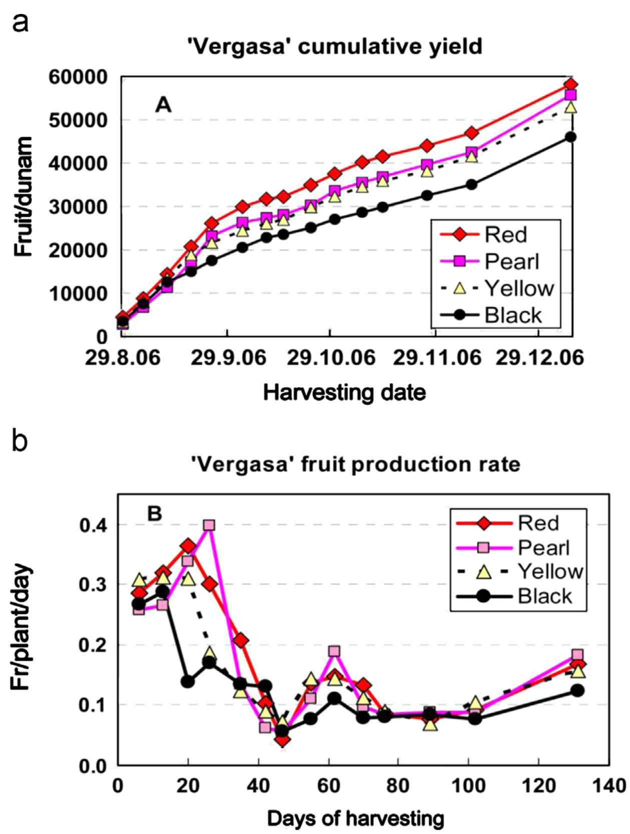

Fig. 10. (a) The cumulative fruit yield (number of fruits harvested per 0.1 ha), (b) fruit production rate (number of fruits/plant/day) in "Vergasa" pepper, under the colored vs. black net during the 2006 season at the Besor experimental station [14]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

respectively. Pepper cultivation under the colored shade nets had an increased productivity (5 different cultivars were tested during 3 successive years). Depending on the year and the cultivar, the total fruit yields (in t/ha per season) under the colored nets were higher by 115–135%, relative to the equivalent black shade net. The higher fruit yield resulted mostly from the enhanced rates of fruit production (number of fruits produced per plant: Fig. 10(a) and (b)). The increase of the productivity could be attributed to the modification of the light quality by the tested photoselective shade nets, the higher content of scattered/diffuse light under these nets compared with the equivalent black ones, the modified spectral composition. Pearl, Yellow and Red nets all transmitted highly the scattered light which was enriched in the green+red+far-red spectral range relative to the UV+blue (Fig. 9).

2.7.3. *Critical issues*

Energy saving is important for the northern countries with cold winters. For these cases extra insulation by an extra layer of cover leads to decrease of light transmittance, and thus may affect negative crop production. Thereby, when this specific type of cladding is considered for practical applications, attention should be paid to the light transmission.

Regarding photoselective nets, factors such as net color, porosity, shading factor and solar angle, influence the transmittance in the UV, PAR and visible light wavelengths and thus, should be taken into consideration [53]. Finally it should be mentioned that when sunlight is optimized (for example by means of the above mentioned specific claddings or in general with another specific covering), it can still be necessary to add artificial light to ensure a year-round production [54].

3. Additional considerations

Following are given some additional considerations which are of interest and are related with investigations about greenhouse claddings (or in general about greenhouses).

3.1. *Cladding degradation*

Russo et al. [55] studied the influence of natural and accelerated weathering on the performance of photoselective greenhouse films. The effect of the weathering on PE-based films was investigated. Monolayer films of low density/linear low density PE blends, containing commercially available organic pigments and an UV absorber of the benzophenone type, were examined. The samples were weathered on field (natural weathering) or by using two different artificial procedures: UV lamp and QUV chamber. The conditioned film samples were, then, analyzed by performing several physical tests. The rheological measurements revealed an increase in the viscosity of the weathered sample melts as a consequence of photodegradation phenomena, inducing the formation of double bonds and crosslinks. The latter result was also confirmed by gel content measurements. UV–visible spectroscopic tests showed that in both cases (of natural and artificial weathering) an increase of the transmittance of films occurred. Tensile tests indicated the increase of films stiffness, especially in case of samples conditioned using the UV lamp and a large decrease of the strain at break, both in machine and in transverse directions, especially for film weathered using the QUV chamber.

Furthermore, Dehbi and Mourad [56] conducted a comparative study about the durability of mono-layer versus tri-layers LDPE films used as greenhouse cover. The degradation and fracture behavior regarding the abrasion of that generation of polymeric greenhouse covers presenting a sandwich structure made of three layers of LDPE was studied and compared with that obtained from monolayer film (often used in North Africa for plasticulture devices). The results showed that the degradation performance of these tri-layers films was quiet better than that of the monolayer film, in terms of the mechanical and surface energy properties. The lifespan of these films under natural conditions in the north of Algeria was estimated to be 10 and 5 months for the tri-layer and mono-layer films, respectively.

In addition, Dehbi et al. [57] conducted a study about the artificial ageing of tri-layer polyethylene film used as greenhouse cover under the effect of the temperature and the UV-A simultaneously. The increase in the free surface energy was found to be proportional to the temperature and the increase was more pronounced when the film was subjected to the combined action of the temperature and the UV-A radiation. The mechanical tests showed that both elongation at break and yield stress decreased with the ageing. The calorific curves showed two endothermic peaks of melting close together (100 °C and 110 °C) which revealed the presence in the film of at least two types of crystalline structures. From free surface energy results, the life time of these films under artificial conditions was estimated to be 12 months when exposed to 40 °C while it dropped to 3 months and 18 days when exposed simultaneously to 50 °C and UV-A.

3.2. *Greenhouse microclimate*

The radiometric properties of greenhouse cladding are related with the amount of energy that enters through the covering material and thus, influence the microclimate inside the

greenhouse. In the literature there are studies which regard the relationship between the cladding material, the greenhouse microclimate and the spectral distribution of the light.

Kittas et al. [58] investigated the influence of greenhouse covering materials and shading on the spectral distribution of light in the greenhouse. The results revealed the importance of a more precise characterization of modifications in light quality induced by greenhouse materials or shading devices as plant photosynthetic and photomorphogenetic responses may be significantly influenced by these modifications. Moreover, the classical greenhouse cover material or shading techniques which are generally considered as neutral with respect to light distribution, may affect significantly some light quality parameters (mainly blue light-related parameters) while being almost neutral for others (the phytochrome-related parameters) or inducing minor changes in the photon flux ratios for the PAR to NIR and for the PAR to TOTAL wavebands. Conclusively, the findings showed the importance of detailed in situ characterization of the light environment when new cover materials are proposed by glass or plastic manufacturers particularly in the case of selective, fluorescent or colored cover materials.

Mashonjowa et al. [59] studied the effect of covering material on the greenhouse microclimate of rose plants. Measurements of the radiometric properties of plastics used as covering material of greenhouses in Zimbabwe were taken, under laboratory conditions as well as in an operational greenhouse. Significant differences were found between the transmittance of the plastic films used as covering materials for Zimbabwean greenhouses. The conventional PE films showed transmittances in the solar radiation and PAR wavebands similar to those of glass. However, their transmittances in the thermal waveband were up to 70–90% higher than those for DPE films and glass, respectively. The diffusive PE films had up to 25% lower transmittances in the solar radiation and PAR wavebands than glass and LDPE films. The Gembloux Dynamic Greenhouse Climate Model adequately simulated the internal greenhouse microclimate from outside climate data. It was shown that all the plastic films discussed could perform well and could be considered quite suitable for greenhouse covering materials, depending on the desired application. Diffusive PE films resulted in plant conditions not much different from those obtained under glass films. However, conventional PE films led to leaf temperature relatively lower than the air temperature, making them less suitable for cases such as cold months and disease management. The model showed that the change in radiometric properties of plastic films over a period up to 3 years had a negligible effect on plant microclimate.

3.3. Economic aspects

Some crucial factors which should be taken into account when selecting a greenhouse cover are: (1) the initial purchase price of the cladding, (2) its useful life, and (3) its maintenance and repair. The length of the useful life of a cover is not always easy to be determined because is related with the material conditions of use, the quality of the material (which is not always known from the beginning). For the case of the long-life materials, the annual maintenance cost should also be taken into consideration [60]. Following are given some economic assessment works which regard in general the field of greenhouses (without focusing on the claddings).

In the literature there is a study about the environmental and economic assessment of protected crops for four European Scenarios [61]. That study regards the evaluation of the environmental and economic profile of several agricultural practices for greenhouse crops, in cold and warm climates in Europe, for four scenarios: tomato crop in a plastic greenhouse in Spain, and in glasshouses in Hungary and the Netherlands, and rose crop in a glasshouse in the Netherlands. Cost–benefit analysis was adopted for the economic assessment. Dutch reference systems used a combined heat and power (CHP) system for the production of thermal energy and electricity. The main environmental burdens in the four scenarios were: energy consumption, greenhouse structure, fertilizers. The results showed that the best economic perspectives to reduce inputs are energy savings in glasshouses and reduction of fertilizers in Spain and Hungary. In addition, Manzano-Agugliaro and Cañero-Leon [62] applied utility functions to Mediterranean greenhouse crops and it was proved that they are useful for their economic and environmental analysis. Greenhouse crops in the western coastal of Almería (Spain) have consumption of water, nitrogen and labor close to the optimal.

Finally, it should be noted that there are some economic studies about greenhouse food production in Iran: Mohammadi and Omid [63] conducted a study about greenhouse cucumber. The energy balance between the input and the output per unit area for greenhouse cucumber production was examined. The data of 43 cucumber production greenhouses in the Tehran province, Iran, were collected and analyzed. An econometric analysis indicated that the total cost of production for one hectare of cucumber was around 33,425.70$. Heidari and Omid [64] studied energy use patterns and econometric models of major greenhouse vegetable productions in Iran. The results showed that among the surveyed greenhouses, tomato cultivation was more profitable. Moreover, Banaeian et al. [65] conducted an energy and economic analysis of greenhouse strawberry production in Tehran. The results showed that among the cost inputs, transportation is the most important input which influences the total cost of production, followed by labor, fertilizers and installation of equipments.

3.4. Tendency of the studies/future prospects

General about the tendency of the greenhouse studies regarding solar radiation transmission: there is a potential for further understanding and predicting light distribution patterns in greenhouses. A useful tool towards this direction could be the development of models. In the literature there is a study about the numerical simulation of solar radiation, air flow and temperature distribution in a naturally ventilated tunnel greenhouse [66]. The effect of solar radiation distribution in a typical agricultural building was numerically investigated, taking into consideration cover thickness, its spectral optical and thermal properties. The results revealed that cover materials with high absorptivity deteriorated the natural ventilation increasing the air temperature by convection and favoring the development of secondary recirculation (where the air is trapped). Moreover, the high absorptivity led to reduction of the available PAR but it distributed it equally inside the greenhouse. In addition, the ability of the material to transmit the solar irradiance in the wavelengths corresponding to PAR with comparable absorptivity, improved as the refractive index decreased. In general terms, Computational Fluid Dynamics (CFD), numerical analysis/simulation tools of fluid flow processes are useful for the improvement of several crop farming systems including greenhouses [67].

Another field of research which shows interest is the integration of greenhouses in urban areas in symbiosis with houses. Zaragoza et al. [68] conducted a study about a greenhouse which was incorporated as part of a humid air solar collector system in which the heat collection process allowed for gray water purification and edible biomass development. The system produced water of higher quality than standard biological treatment methods. The greenhouse was part of the collector surface while offered further advantages such a supplementary living space and an integrated food production system. The considerations of Section 2 about the

several cladding materials could be useful also for this type of applications. Certainly, the selection of the appropriate type of cover can facilitate the symbiosis of a greenhouse with a building in an urban area.

On the other hand, technologies which have to do with the pest control by using certain kinds of cladding materials and the support of organic agriculture are also important. For example, UV-blocking claddings are a challenging solution for Integrated Pest Management (IPM) in greenhouse-grown crops and are related with the wavelength-dependent behavior of the insects. There is a positive correlation between the amount of UV filtration and the level of protection against insects (because insects fail to orient themselves within the UV-deficient environment). Nevertheless, these claddings should be used after a preliminary testing for cases such as: when bumblebees are used as pollinators; when the crops are eggplants or other purple plants; when for the pest control beneficial insects are utilized [3]. NIR-blocking claddings for the reduction of the temperature in greenhouse interior space are another option. However, several considerations should be addressed when these coverings are used such as the reduction of the PAR [3]. Furthermore, some of the claddings which are presented in the present work such as photoselective, FSCs, anti-condensation, covers which diffuse sunlight are also important, provided that they are used in a cost-effective way and the appropriate (in each cases) critical issues are considered. Finally, the use of eco-friendly materials for crop protection [69] is another interesting option given nowadays environmental concerns.

At this point it should be noted that in the category "tendency of the studies/future prospects", the application of renewable energy technologies such as solar energy systems, certainly is included. These systems are presented separately in the following section, Section 3.5.

3.5. Solar energy systems

Recent developments regard the use of FLs as alternative claddings [70,71]. Linear FLs are lenses much thinner than conventional and can be integrated at the south roof of a greenhouse. FLs have the ability to separate beam from diffuse radiation and can be combined with Concentrating Photovoltaic Thermal (CPVT) systems [71]. In the frame of FL greenhouses, there are some critical issues which should be taken into account. For example the use of 2-axis tracking has several disadvantages such as increased cost, necessity for more accurate electronic control and greater mechanical loads. Therefore, a concentrator which could be combined with 1-axis tracking is an alternative solution for the reduction of the cost as well as for the reduction of the mechanical requirements. In general, in order to compensate the cost and the efficiency, the use of FLs combined with simple Concentrating Thermal (CT) systems and with 1-axis tracking; for light/temperature control and production of heat; could be a cost-effective solution [3]. More details about this specific type of cladding can be found at authors' previous study [3].

In terms of the solar energy technologies, another option is the use of non-concentrating PVs. Pérez-Alonso et al. [72] studied a PV greenhouse (Almería: South Eastern Spain). A greenhouse roof (9.79% coverage ratio) with 24 flexible thin film modules, was installed in two different checkerboard PV configurations. The yearly electricity production normalized to the greenhouse ground surface was 8.25 kWh/m^2. In addition, Kadowaki et al. [73] studied the effects of shading caused by the PVs of the greenhouse, on onion growth. Welsh onion (*Allium fistulosum* L.) was cultivated by hydroponics. Two PV-array configurations were tested: straight-line and checkerboard. For each configuration, the PVs covered 12.9% of the greenhouse roof. Welsh onion was also cultivated in a control greenhouse. The results showed that the checkerboard PV configuration caused shading intermittently during growth. In this way, the inhibitory effects of the PV-array shading were diminished. The electrical energy generated by the PV checkerboard system was comparable to that of the PV straight-line case. Other studies, in the field of solar energy systems for greenhouses, regard solar cooling [74], PV thermal systems [75] and solar collectors combined with phase change thermal storage units [76].

At this point it should be noted that the applicability in practice and the cost-effectiveness of the proposed systems are critical factors and should be taken into consideration. Another important aspect has to do with the climate of the region where a greenhouse is installed: for example for the specific case of the Mediterranean greenhouses, certain agricultural practices should be adopted [77]. Furthermore, the reduction of greenhouses energy consumption by means of e.g. structural considerations, sealing of the greenhouse envelope, insulation, use of passive solar systems etc. [78], is also crucial.

Conclusively, the application of new, promising, cost-effective, practically applicable solar energy systems is desirable and could have a positive contribution towards the development of eco-friendly greenhouses.

4. Conclusions

In the present paper, several types of greenhouse covering materials which can cause sunlight manipulations are critically presented. Thus, a complete picture of the studied categories is provided; along with the studied issues in authors' previous work about Fresnel lenses (FL), NIR- and UV-blocking materials [3].

In the frame of the present study, photoselective covers which alter Red/Far-red (R/FR), Blue/Red (B/R), Blue/Far-red (B/FR) ratios are presented. These claddings have been proved to be as effective as chemical growth regulators in controlling plant height for example of chrysanthemum and bell pepper seedlings. Two basic categories: plastic films and fluid roofs are examined. Photoselective claddings may include covers with incorporated pigments which have the ability to modify the light spectrum which enters the greenhouse. Thereby, photosynthesis as well as photomorphogenesis and thus plants growth are influenced. Nevertheless, issues such as pigments cost and the integrability of the systems (for the case of the fluid roofs) into the greenhouse should be examined.

In terms of the Fluorescent Solar Concentrators (FSC), fluorescent dyes can be incorporated into greenhouse plastic covers. These dyes convert light for example from the green part of the spectrum into red light. Several studies showed that FSCs result in increase of crop yield. The solar photons which enter the FSC plate are absorbed by the luminescent species and reemitted in random directions. The trapped photons are transferred to the edges where Photovoltaic (PV) cells can be placed. The possibility of combining FSCs with PVs (and thus the parallel production of electricity) is an interesting option. Certainly, when considering the feasibility of FSC claddings, factors such as the cost of the pigments which are added in the cladding should be taken into consideration.

On the other hand, there are few studies in the literature about passive optical means. These studies are not recent and this could be attributed to the low effectiveness of this type of systems. Thus, the practical applicability of these claddings is crucial and it should be addressed.

In addition, in the literature there are some studies which refer to solar stills integrated into greenhouses for cultivation in places where saline or brackish water is available. This type of roof also reduces solar energy transmission and protects plants from excess sunlight. However, for this type of systems factors such as the

quality of the transmitted light as well as the economical feasibility should be taken into consideration.

Another category includes the anti-drip claddings since the presence of condensate on the interior surface of the greenhouse cover alters cladding transmittance over the PAR range. This condensation of water is associated with several negative effects on plant growth and quality (e.g. reduction of light transmission, increase of certain diseases). Anti-drip claddings can be films which contain specific additives for the elimination of the droplets. These films, provided that they are used properly, offer advantages such as more light in the greenhouse interior space, higher yield of the plants, better quality of the plants, reduction of diseases. However, the ventilation (and/or the heating) of the greenhouse combined with adequate inclination of the roof, are critical factors. Also the anti-drip effect is reduced as time passes because it is possible the additives to be washed out by the run-off water. Moreover, in some cases of greenhouses with anti-drip films, fog could be created in the greenhouse interior space which means that ventilation (and/or heating) is necessary immediately.

On the other hand, there are claddings which have the ability to diffuse the light. For that case, the seasonal variation of solar radiation as well as plant development are crucial factors and can affect the light distribution in greenhouse interior space. These covers may offer several choices of levels of diffusion (low, medium, high); the most appropriate choice depends on the climate of the greenhouse installation area, the crop and the season of growing.

Furthermore, double cladding techniques provide a solution for the reduction of greenhouse losses and thus for the reduction of greenhouse energy consumption. Other coverings for energy savings are the plastics with zigzag double-web structure which combine high light transmittance with good thermal insulation. These techniques of energy savings are of importance for countries with cold winters but attention should be paid to the light transmission.

Photoselective nets are another type of cladding and can be used in greenhouses in order to achieve the desired physiological responses of the cultivated plants as well as for disease control. Aspects such as net color, porosity, shading factor, solar angle influence of the transmittance in the UV, PAR and visible light wavelengths should be addressed. It should be mentioned that when sunlight is optimized (e.g. by means of the above mentioned specific covering or in general with another specific cladding), it can still be necessary to add artificial light in order to ensure a year-round production.

For all the types of coverings, some additional considerations include: cladding degradation; the relationship between greenhouse microclimate and cladding material; economic aspects; light distribution patterns in the greenhouse. Conclusively, in terms of the presented types of greenhouse covers, factors such as their practical applicability, cost effectiveness, the kind of the cultivation as well as the climate of the region, are crucial and should be addressed. Finally, another important aspect is the development of energy efficient greenhouses and the application of renewable energy technologies such as solar energy systems.

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